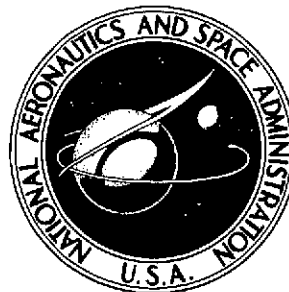


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# EFFECT OF STRAIN HARDENING ON FRICTION BEHAVIOR OF IRON LUBRICATED WITH BENZYL STRUCTURES

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16. Abstract <p>Sliding friction experiments were conducted with iron, copper, and aluminum in contact with iron in various states of strain. The surfaces were examined in dry sliding and with various benzyl compounds applied as lubricants. Friction experiments were conducted with a hemispherical rider contacting a flat disk at loads of from 50 to 600 grams with a sliding speed of 0.15 cm/min. Results indicate that straining increases friction for dry sliding and for surfaces lubricated with certain benzyl structures such as dibenzyl disulfide. With other benzyl compounds (e.g., benzyl formate), friction coefficients are lower for strained than for annealed iron.</p>					
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# EFFECT OF STRAIN HARDENING ON FRICTION BEHAVIOR OF IRON LUBRICATED WITH BENZYL STRUCTURES

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## SUMMARY

An investigation was conducted with iron, copper, and aluminum sliding on iron that had been strain hardened to various degrees. Friction coefficients were measured for sliding in the dry state and with various benzyl compounds applied to the iron surface to act as lubricants. A hemispherical rider contacted a flat iron disk at loads of from 50 to 600 grams with a sliding velocity of 0.15 centimeter per minute. The iron flats were of various hardnesses, from Rockwell B 26 to 80. The lubricants included benzyl ether, alcohol, chloride, amine, sulfide, disulfide, and formate.

Results indicate that strain hardening of iron affects friction behavior both for the unlubricated and the lubricated surface. Straining results in increased friction for dry sliding and with certain of the benzyl compounds such as benzyl disulfide. With other lubricants such as benzyl formate, friction at higher loads is less for the strained iron than it is for iron in the annealed state. Of the benzyl structures, benzyl chloride was the most effective in reducing friction.

## INTRODUCTION

A wide variety of organic compounds containing surface active groups or atoms have been used as extreme pressure lubricant additives. The surfaces with which these additives most frequently interact are gear or bearing steels. Since steels are principally iron, the basic chemical reactions that occur between the additive and the steel surface result in the formation generally of iron inorganic compounds or organometallics.

Steel surfaces of bearings and gears that interact with lubricant additives are generally in a stressed state. Further, in metal working operations, the metal undergoes a high degree of straining. The fundamental effect of residual stresses and straining on the lubricated friction behavior of iron has generally not been studied (ref. 1). It might

be anticipated that residual stresses and strain would affect friction behavior.

The objective of this investigation was to determine the influence of strain hardening on the friction of iron surfaces lubricated with various lubricant additives. The additives examined were all benzyl compounds containing varied surface active groups. Annealed iron strain hardened to various degrees was studied in sliding friction experiments. A film of the lubricant additive material was applied to the iron surface before the commencement of sliding. Friction experiments were conducted with a hemisphere sliding on a flat under applied loads of from 50 to 500 grams and at a sliding velocity of 0.15 centimeter per minute.

## MATERIAL AND SPECIMEN PREPARATION

The iron used in this investigation was 99.95 percent pure with the principal impurity being carbon. The specimens to which the lubricant film was applied were 3 by 3 by 0.3 centimeter. The rider specimens were hemispherically tipped with a 0.3-centimeter radius.

All of the benzyl compounds were reagent grade materials. They were used as received. No attempt was made to further purify the material.

The iron specimens were polished with metallurgical papers down to 600 grit and were then electropolished in a solution of 60 cubic centimeters of perchloric acid in 500 cubic centimeters of ethyl alcohol. Strain was introduced into the iron flats by pressing them in a hydraulic press just before the electropolishing. The applied pressures were sufficient to produce a range of specimen hardnesses from Rockwell B ( $R_B$ ) 26 to 80. The applied pressures and resulting hardnesses are presented in table I.

The rider specimen of iron was used in the machined state after electropolishing. It has a hardness of  $R_B$  43.

## PROCEDURE

After electropolishing the iron specimens were placed in a quartz tube, which was evacuated with a vacuum pump. The specimens were heated while in vacuum to just below the recrystallization temperature of iron in order to drive adsorbates from the surfaces. On cooling to room temperature, the lubricant additives were admitted to the evacuated vessel. The specimens were then removed from the vacuum with a lubricant film on their surface and transferred to the friction apparatus. All friction experiments were conducted under a blanket of argon gas. A slight positive argon pressure was maintained in the plastic box housing the friction apparatus.

Some of the lubricants used in these studies were liquids and others were solids. The

liquids were admitted to the evacuated vessel containing the iron samples by means of a hypodermic syringe. The needle was stuck through the rubber stopper of the evacuated vessel. The vacuum of the vessel drew the liquid out of the syringe. After the liquid outgassed the vacuum system was shut off and the iron specimen was in a saturated vapor of the liquid.

With the solid lubricants, a small amount of the solid was placed in the vacuum vessel with the iron before evacuation. After evacuation the solid at the base of the tube was heated to liquification. It vaporized in the vacuum and condensed on the iron sample which was suspended in the center of the vessel. It condensed as a liquid on the iron surface.

## APPARATUS

The apparatus used in this investigation is shown schematically in figure 1. The apparatus was basically a microscratch hardness tester to which a drive motor with a gear reduction head was attached to provide uniform motion, at various speeds, of the surface under examination.

The rider specimen was mounted on an arm above the iron flat surface. Loading was accomplished by the application of dead weights directly over the iron rider. The arm retaining the iron rider specimen had a strain gage assembly for monitoring frictional force.

All experiments consisted of a single pass across the iron flat surface. The total distance of travel was approximately 20 millimeters.

The entire apparatus was enclosed in a clear plastic box. The box was purged with argon for 20 minutes before each experiment. During the experiment, a slight positive pressure was maintained in the box.

## RESULTS AND DISCUSSION

A relatively common concept regarding the friction behavior of metals is that harder metals exhibit lower friction coefficients than softer metals.

To test this concept dry iron was slid on iron that had been strain hardened various amounts. Only the iron flat was strain hardened. The iron rider had a hardness of  $R_B$  43 in all experiments. The rider could, however, strain harden with sliding. Some typical results obtained are presented in figure 2.

The data of figure 2 indicate that strain hardening elemental iron results in an increase in friction coefficient. Steady-state friction was at the minimum for the completely annealed iron. For iron in the strained state there is a large amount of stored

energy which can contribute to adhesive bonding. A metal in a higher energy state (strain hardened) may exhibit stronger metallic adhesive bonding than that same metal in a lower energy state (annealed). Thus, the results of figure 2 are as might be anticipated.

The results of figure 2 might be likened to those of the influence of crystallographic orientation on friction behavior. With metal crystals, the highest atomic density, lowest surface energy planes exhibit the lowest friction, while the lowest atomic density, highest energy planes exhibit the highest friction.

In figure 2 iron was in sliding contact with iron. Also, both aluminum and copper riders were slid across iron flats strained to various hardnesses. In all cases of dry sliding aluminum and copper were transferred to iron. The amount of metal transferred was strongly affected by the degree to which the iron had been strain hardened. The greater the degree of strain hardening, the greater the amount of copper and aluminum seen on the surface. Figure 3 indicates the transfer of aluminum to strain hardened iron.

Figure 3(a) is a scanning electron micrograph of aluminum transferred to iron; an X-ray dispersive analysis for aluminum on the iron surface is shown in figure 3(b). Note that the concentrations of white spots in figure 3(b) correspond to those locations in figure 3(a) where transfer is seen. The copious amount of aluminum seen in figure 3 is a result of a single pass of the aluminum rider across the iron flat surface.

Transfer of copper to the iron surface is shown in figure 4. In figure 4(a) the scanning electron micrograph indicates the nature of the surface transfer and an X-ray scan for transferred copper in figure 4(b). It is of interest to compare figure 4 with figure 3. Under identical conditions of sliding, there appears to be a larger quantity of aluminum than copper transferred to iron.

Various benzyl compounds were applied as films to an iron surface to determine their influence on friction coefficient (hardness of iron flat,  $R_B 4^0$ ). The results obtained are presented in table II. An examination of table I indicates that the most effective addition to the benzyl structure to reduce friction is to include chlorine in the molecule. With an aluminum rider, benzyl amine gave the same friction coefficient as the benzyl chloride. The iron and copper riders, however, exhibited their lowest friction coefficients in contact with iron when the benzyl chloride was used as the lubricant.

In table I, with benzyl formate, the friction coefficient was identical for all three rider specimens. Thus, the lubricating characteristics of the benzyl formate may result from the interaction of that molecule with the iron flat.

Several benzyl compounds are extreme pressure lubricant additives and are of greatest benefit under heavy load conditions (ref. 2).

To examine the effect of load on the friction behavior of iron sliding on iron, experiments were conducted at various loads, and the effect of load on friction coefficient established. Iron strain hardened to various degrees was also examined as a variable.

Results of friction experiments at various loads for essentially two hardnesses of iron with benzyl formate as the lubricant are presented in figure 5. At light loads

(< 200) load and strain hardening exerted very little influence on friction coefficient. At loads greater than 200 grams, however, an increase in the friction coefficient for the annealed iron was observed. The results of figure 5 do indicate that straining the iron affects the friction behavior with benzyl formate as the lubricant. With unlubricated sliding in figure 2, strain hardening resulted in an increase in friction coefficient. In figure 5 it results in a decrease in friction coefficient.

Benzyl disulfide has been examined extensively as an extreme pressure additive for the lubrication of steel surfaces (refs. 3 to 7). Friction experiments were therefore conducted with benzyl disulfide lubricating iron containing various degrees of strain hardening. The friction coefficients obtained at various loads for iron flats strained to  $R_B$  30, 45, and 80 are presented in figure 6.

The data of figure 6 indicate that strain hardening of the iron has a very pronounced effect on the coefficient of friction measured for iron lubricated with benzyl disulfide. The greater the degree of strain hardening, the higher the coefficient of friction. Iron specimens strained to levels other than those presented in figure 6 correlated with the results of figure 6.

With dibenzyl disulfide (fig. 6) strain hardening resulted in an increase in friction coefficient, and with benzyl formate strain hardening resulted in a decrease in the friction coefficient. Thus, the effect of strain hardening on the friction coefficient of iron on iron is strongly a function of the lubricant specie involved. There is a marked difference in the nature of the lubricant films formed in figures 5 and 6. In figure 5 the benzyl formate, organometallic films are formed on the iron surface, it is these films that lubricate (ref. 8). Benzyl sulfide reacts with iron to form iron sulfide, an inorganic compound (ref. 7). In the single pass across the surface of these experiments this compound may not form.

Sliding friction experiments were conducted with a copper rider contacting flats of iron strained to various hardnesses. Friction coefficient was measured as a function of hardness with various benzyl compounds. Some results are presented in figure 7.

There are two observations to be made from figure 7. First, with all three film materials, benzyl alcohol, benzyl formate, and benzyl sulfide, a decrease in friction coefficient is observed with an increase in the amount of strain hardening. Second, there are marked differences in friction behavior with the three lubricants. The alcohol, which just chemisorbs to the surface, affords the least surface protection, and the sulfide, which forms an inorganic compound, produces the lowest measured friction coefficients.

Although the presence of lubricating films on the iron surface reduced the adhesive transfer of copper to the iron surface, transfer was still observed. Evidence for such transfer with dibenzyl disulfide is seen in the scanning electron micrograph (fig. 8(a)) and the X-ray map of the iron surface (fig. 8(b)). A piece of copper has adhered to the iron in the midsection of the photograph and the X-ray map.

The effectiveness of the benzyl sulfide on the reduction of adhesive transfer of copper to iron can be seen by comparing figure 8 with figure 4. All of the benzyl compounds presented in table I reduced adhesive transfer. Benzyl chloride was, however, the only lubricant with which no transfer of aluminum or copper to iron was observed.

In figure 6 for iron sliding on iron, the effect of strain hardening on the performance of benzyl disulfide was that, with an increase in hardness, there was an increase in friction coefficient. The question arises as to what is the observed effect of hardness when the rider contacting the iron flat is not iron.

Friction experiments were conducted with copper and aluminum sliding against strain-hardened iron lubricated with a film of benzyl disulfide. The results obtained are presented in figure 9. With copper friction decreased with increasing hardness. The friction coefficient, however, remained unchanged when the rider was aluminum. Thus, it is not only the metallurgical state of the iron that influences friction with a particular lubricant, but also the nature of the mating metal surface. Changing the rider material from iron produced markedly different effects with variations in iron hardness of the iron flat.

Figure 10 is a summary of these states of lubrication of iron with various amounts of strain hardening. In the dry state friction increases with increase in hardness. With dibenzyl disulfide friction also increases with sliding. When the iron surface is lubricated with benzyl formate, however, friction decreases with increased strain hardening of the iron flat.

## CONCLUSIONS

Based on the results obtained in this investigation of various benzyl structures lubricating iron, copper, and aluminum in sliding contact with iron which had been strain hardened to various degrees, the following conclusions are drawn:

1. Strain hardening of iron increases the friction of iron to itself in dry sliding.
2. With most benzyl compounds the friction decreased with the strain hardening of iron. An increase in friction, however, was observed with strain hardening when dibenzyl disulfide was the lubricant.
3. Of the benzyl molecular structures examined, the lowest friction coefficients, in general, were obtained with benzyl chloride.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, February 5, 1974,  
502-01.



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TABLE I. - HARDNESS OF IRON  
FLATS RESULTING FROM VARIOUS

APPLIED PRESSURES

Applied Pressure		Resulting Rockwell B hardness
N/m <sup>2</sup>	kg/mm <sup>2</sup>	
(a)	(a)	26
(b)	(b)	40
14.21×10 <sup>6</sup>	1.45	34
28.42	2.90	55
29.40	3.00	57
52.92	5.40	65
58.80	6.00	70
71.54	7.30	74
113.68	11.60	80

<sup>a</sup>Annealed at 600° C.

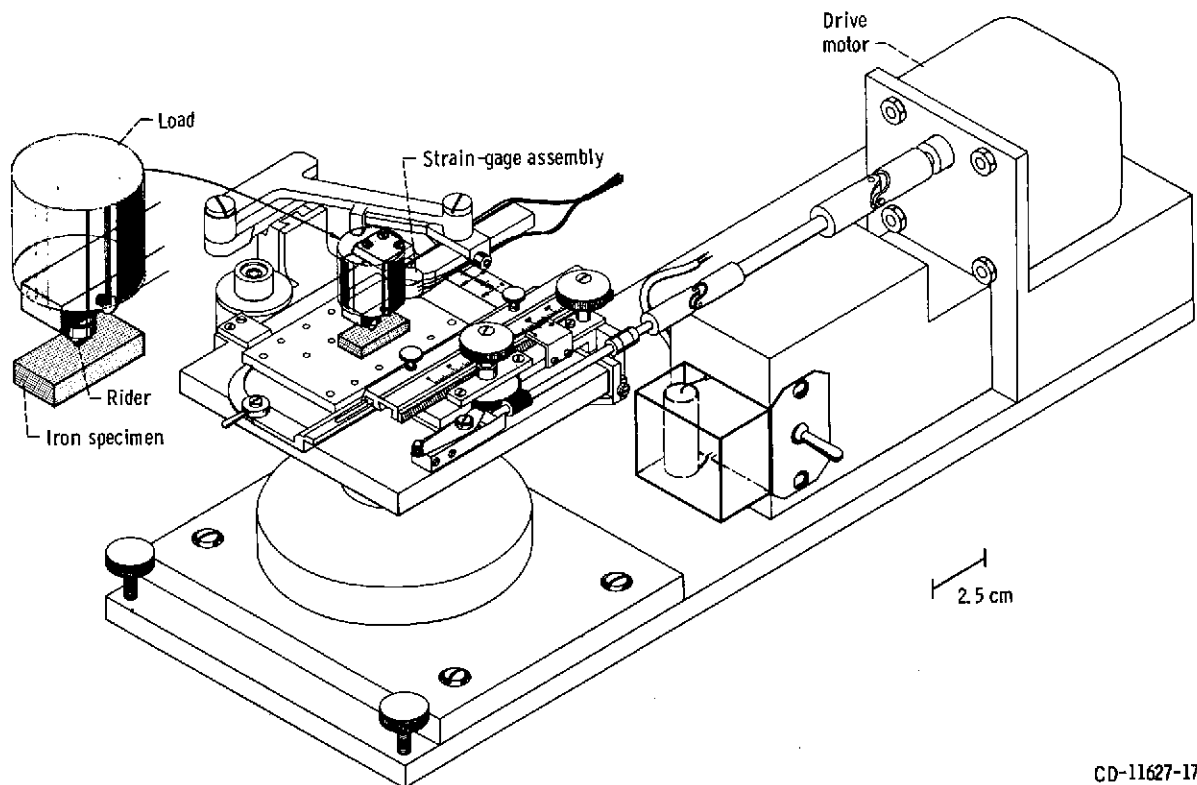
<sup>b</sup>As rolled.

TABLE II. - EFFECT OF VARIOUS BENZYL  
COMPOUNDS ON FRICTION COEFFICIENT  
FOR IRON IN CONTACT WITH

VARIOUS METALS

Benzyl compound	Rider specimen <sup>a</sup>		
	Iron	Aluminum	Copper
Benzyl ether	0.38	0.25	0.25
Benzyl alcohol	.30	.19	.25
Benzyl chloride	.20	.15	.10
Benzyl amine	.25	.15	.20
Benzyl sulfide	.23	.22	.16
Benzyl disulfide	.35	.28	.33
Benzyl formate	.25	.25	.25
Dry state	.35	.33	.25

<sup>a</sup>Same iron flat was used with three rider materials and various lubricants. Flat harness, R<sub>B</sub> 43; load, 200 grams.



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Figure 1. - Sliding friction apparatus.

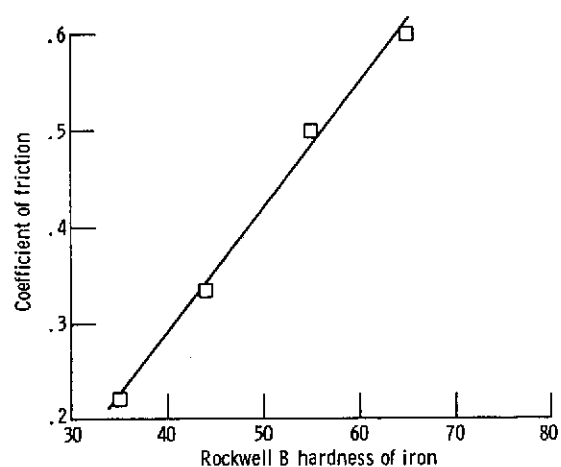
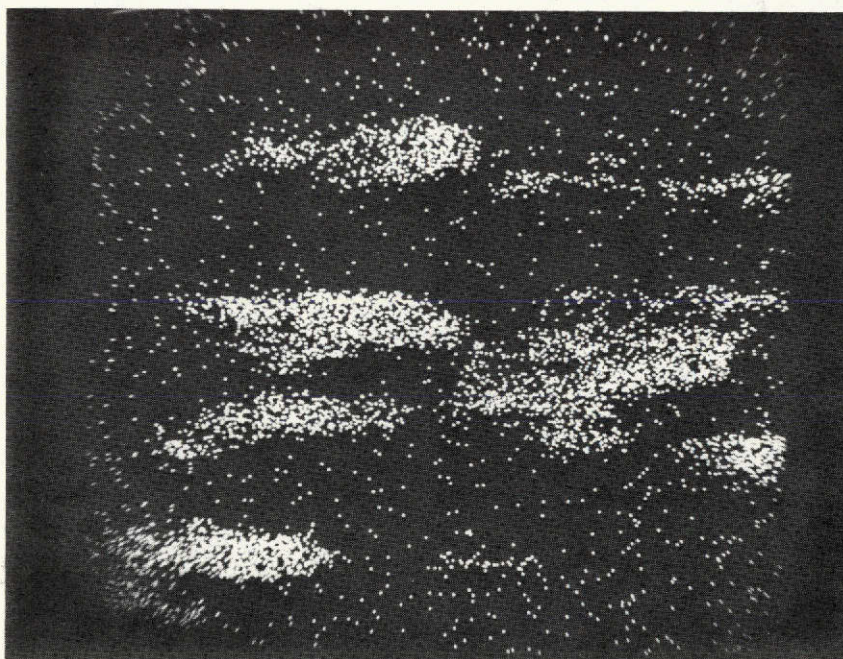


Figure 2. - Coefficient of friction as function of hardness for dry iron sliding on dry iron. Load, 200 grams; temperature, 23° C; sliding velocity, 0.15 centimeter per minute.



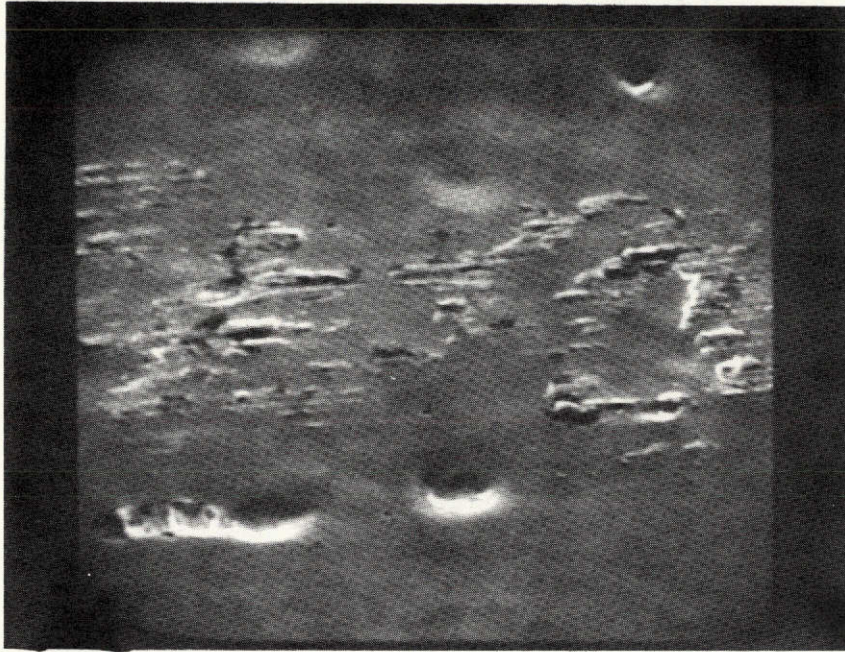
(a) Scanning electron micrograph.



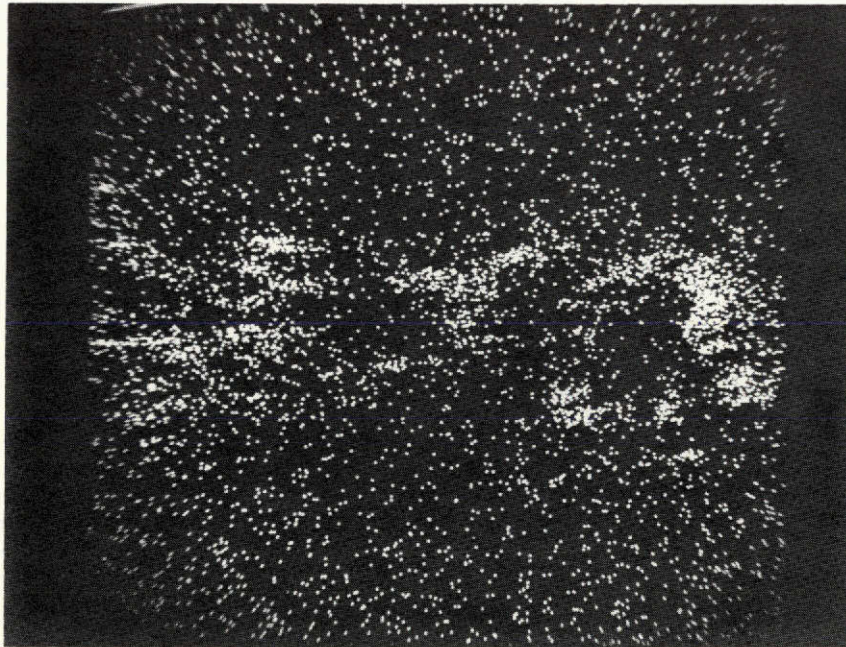
(b) X-ray dispersive analysis map.

Figure 3. - Aluminum transferred to iron after dry sliding. Sliding velocity, 0.15 centimeter per minute; load, 200 grams; temperature, 23° C; single pass.





(a) Scanning electron micrograph.



(b) X-ray dispersive analysis map.

Figure 4. - Copper transferred to iron after dry sliding. Sliding velocity, 0.15 centimeter per minute; load, 200 grams; temperature, 27° C; single pass.

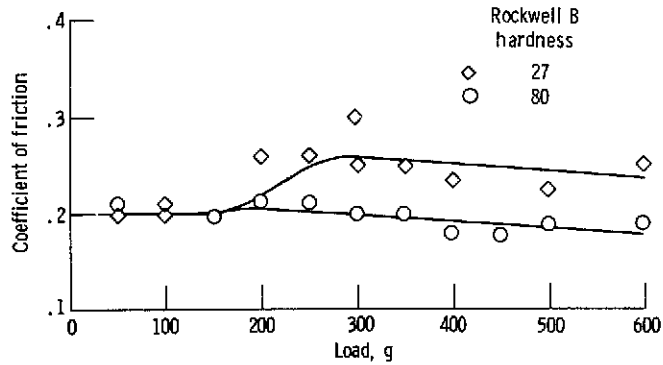


Figure 5. - Coefficient of friction for iron sliding on strain hardened and annealed iron in presence of benzyl formate film.

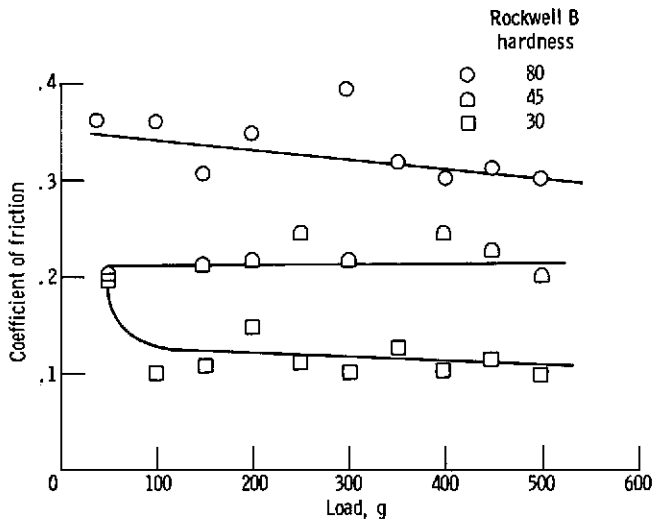


Figure 6. - Coefficient of friction for iron sliding on strain hardened and annealed iron in presence of dibenzyl disulfide film.

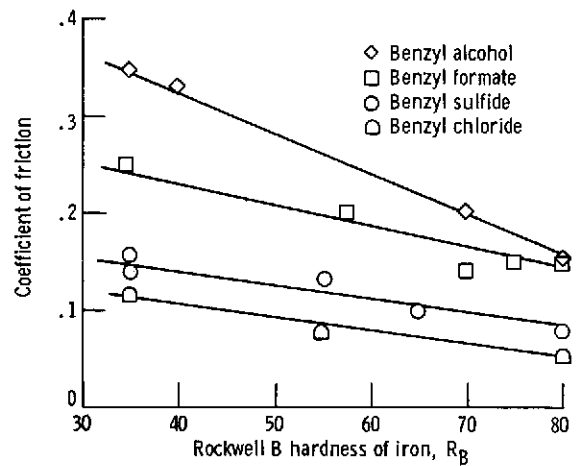
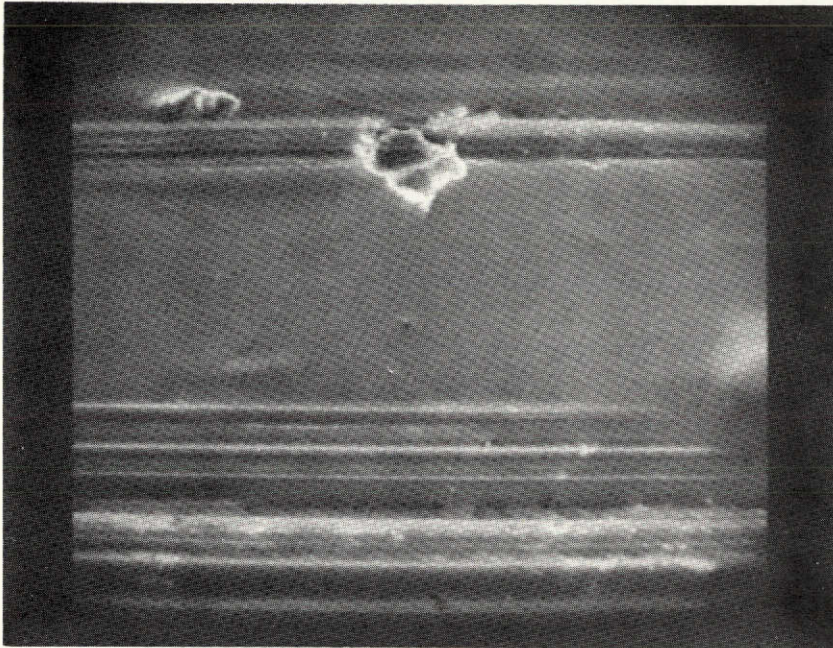


Figure 7. - Coefficient of friction for copper sliding on iron in presence of various surface films. Sliding velocity, 0.15 centimeter per minute; load, 200 grams; temperature, 23° C.





(a) Scanning electron microscope.



(b) X-ray dispersive analysis map.

Figure 8. - Copper transferred to iron after sliding under benzyl disulfide. Sliding velocity, 0.15 centimeter per minute; load, 200 grams; temperature, 23° C; single pass.

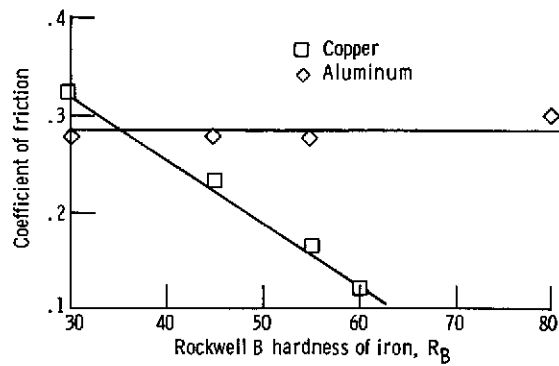


Figure 9. - Coefficient of friction for aluminum and copper sliding on iron in presence of dibenzyl disulfide film. Sliding velocity, 0.15 centimeter per minute; load, 200 grams; temperature, 23<sup>0</sup> C.

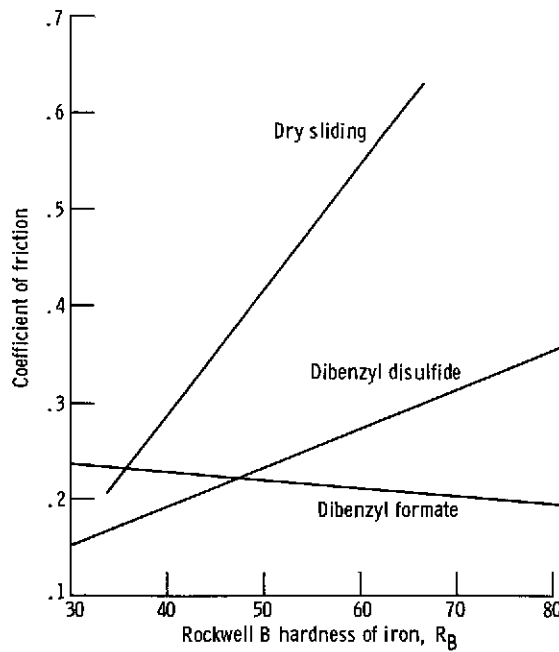


Figure 10. - Effect of strain hardening on friction coefficient for iron sliding on iron with and without lubrication.